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SATELLITE BROADCASTING:
A common-frequency approach to wideband HDTV with a hand-made example 'plan'

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SATELLITE BROADCASTING: A COMMON-FREQUENCY APPROACH TO WIDEBAND HDTV WITH A HAND-MADE EXAMPLE 'PLAN'

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Summary

The generation and analysis of a 'hand-made' plan for satellite broadcasting are described. The plan is intended as an example of what could be achieved within any band which may be allocated for wide-band HDTV at a forthcoming World Administrative Radio Conference.

It is shown that the whole of such a band could be used by every country simultaneously, each country being assigned an orbit location and the use of one or the other hand of polarisation, provided digital modulation is used with receiving antennas of sufficient directivity.

As a guide, 0.9 m at 17 GHz or 0.7 m at 22 GHz appear to be adequate receiving-antenna diameters as far as controlling interference is concerned. Use of digital modulation in this way makes more efficient usage of spectrum than analogue modulation, offering more programmes per country per MHz of allocated band. It also permits greater flexibility of exploitation of the band.

Index terms: *DBS; HDTV; planning; digital modulation; frequency band; SHF; CCI; digital TV signals; antenna-Rx*

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SATELLITE BROADCASTING: A COMMON-FREQUENCY APPROACH TO WIDEBAND HDTV WITH A HAND-MADE EXAMPLE 'PLAN'

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1. INTRODUCTION

There is currently much interest in HDTV. An essential element in the chain is the means by which it is to be delivered to the viewer. One candidate is satellite broadcasting. The 12 GHz band has already been allocated to the Broadcasting Satellite Service (BSS) and planned on the assumption of analogue FM transmission of the familiar PAL/SECAM/NTSC standards. For Europe, Africa and Asia this planning took place at the World Administrative Radio Conference[1] of 1977, commonly called WARC-77. Fortunately it was possible to show that the various members of the MAC family could fit within the Plan, and more recent work has established that this is also true for HD-MAC, which is what is called "narrow RF band HDTV" in CCIR language. Thus, to the extent that channels are available within the WARC-77 Plan, there is a potential outlet for the first phase of HDTV.

In the longer term there will be a demand for more. "More" means more programme channels, but also more quality. This is what the CCIR calls "wide RF band HDTV" will come into being. Unfortunately there is not as yet any suitable frequency allocation to the BSS in Europe which could answer this demand. There is however an allocation around 22 GHz available elsewhere in the world and there has been considerable pressure to obtain an allocation for Europe of at least comparable scope. As a result of this pressure and the reporting of many studies (e.g. Ref. 2), the WARC of 1988 recognised that the problem of finding an allocation should be put to a future conference (now known to be scheduled for 1992) which will be competent to modify the International Frequency Table.

The use of a rigid plan for the 12 GHz band has made it difficult to develop readily. It is not easy to introduce new services which were not foreseen at the time of the plan.

Although the concept of a rigidly pre-planned use of a BSS band has therefore become less fashionable, planning exercises are nonetheless useful in order to determine how much use can be had from each MHz of spectrum allocated to the BSS. Only by combining this result with the demand for programmes can the bandwidth needed for a new allocation be determined in a way which can be supported at a WARC in the face of counter-arguments from all the other claimants for spectrum. Methods which show the usage of spectrum to be particularly efficient should assist the presentation of the case for a new band for HDTV.

Some preliminary planning exercises have been done for both analogue and digital systems, by the EBU[2] and also by BBC Research Department under sub-contract to British Aerospace as part of an ESA study[3]. Some results of the latter study suggested that for digital systems, which are relatively tolerant of interference, it might be possible to use a strategy in which all the band is allocated simultaneously to all service areas. This technique has been called a "single-frequency plan", but is referred to here as a "common-frequency plan" to avoid confusion with the nearly-eponymous "single-frequency network" which is now well established to describe something rather different which arises in terrestrial digital audio broadcasting (DAB).

The ESA study of such common-frequency possibilities considered more-or-less regular patterns of coverage areas for simplicity, and thus could be considered academic and perhaps over-optimistic, because real countries have irregular borders and inhomogeneous sizes.

This Report describes some work which considers the coverage of real countries — virtually all of Europe and Africa — using a common-frequency plan. It will be seen to be very attractive.

2. PLANNING STRATEGIES

In order to accommodate a large number of users into a frequency band of restricted bandwidth it is necessary to use some type of frequency re-use. In other words, there is more than one transmission on the same frequency. Mutual interference must be kept down to an acceptable level, usually specified in the form of protection ratios — the minimum acceptable ratio of wanted signal to interfering signal. This is achieved by exploiting various possible mechanisms. These include transmitting-antenna discrimination (corresponding to the geographical separation of the service areas), receiving-antenna discrimination (corresponding to the separation between satellites around their orbit), use of both hands of polarisation, and finally frequency separation. Planning is the art of juggling all of these in a way which satisfies the demands for services within constraints of performance and total spectrum.

2.1 WARC-77

As previously noted, WARC-77 was based on analogue FM transmission. In this case the co-channel protection ratio (31 dB) is too high to achieve reliably using only one of the above factors (other than a very large frequency separation). Furthermore, the adjacent-channel protection ratio depends on the frequency spacing between channels. Studies showed it was best if channels overlapped somewhat. The closer the channel spacing, the more channels can be accommodated within a fixed bandwidth, and thus less services need share the same channel. On the other hand, as the channels become closer, the amount of interference from an adjacent channel which can be tolerated decreases. The 1977 Plan ended up with 27 MHz nominal channel width together with 19.18 MHz channel spacing. Thus within the 800 MHz available within the 12 GHz BSS band in Europe, there are 40 channels.

WARC-77 accommodated a number of special requirements; neglecting these, and considering only Europe and Africa, several patterns emerge.

(a) The same channel is never re-used with the same polarisation from the same orbital slot. This is because the co-polar pattern of the transmitting antenna does not provide sufficient discrimination when compared with the CCI protection ratio. (Remember that all sources of interference combined together must satisfy the protection ratio, so in general each individual interferer needs a margin of safety).

(b) The same channel can be re-used, from the same orbit slot, to serve a physically-remote service area with the opposite hand of polarisation. This is because the cross-polar pattern of the transmitting antenna lies below its co-polar pattern. In the Plan, European countries share with Central or Southern African countries in this way.

(c) Physically-adjacent areas can be served from the same orbit location if they are adjacent-channel and cross-polar, or co-polar with greater frequency separation. Here frequency discrimination supplements the antenna discrimination.

(d) Physically-adjacent areas may be served from separated orbit locations if they are co-polar and adjacent-channel. Here the receiving antenna discrimination is supplemented by frequency separation.

(e) In most cases the orbit slot was chosen well to the West of the service area for eclipse protection. The satellite's solar cells would thus be eclipsed by the Earth after local midnight, during the restricted part of the year in which eclipses occur.

(f) The larger countries were divided into smaller beams, partly to reflect regional differences but mostly in recognition of the high transmitter powers that would be required to provide the same EIRP to such large-area beams.

(g) No beam was given a smaller diameter or minor axis than 0.6° (primarily because the transmitting antenna would become too large, and also partly in recognition of the pointing error assumed, namely ± 0.1°, and 2° of rotation).

(h) Virtually all countries (or regions within very large countries) ended up with 5 channels.

The Plan was done in a regular fashion so that an allocation for say channel 3 is repeated on channels 7, 11, 15 & 19. The upper (channels 21-40) and lower (channels 1-20) halves of the Plan were kept essentially separate — it had been thought that wideband receivers for the whole 800 MHz would be too expensive. Asia (ITU Region 2) only has 32 channels so a different structure applies.

2.2 Other ideas

The fact that digital modulation is somewhat more tolerant of interference[4] has led to some different proposals (an example of the ruggedness of digital modulation systems employing coding techniques is given in Appendix 1). One idea[5] is that channels should no longer overlap and both hands of polarisation can be used from one orbit slot to serve the same service area on the same channel. Of course, isolation from neighbouring service areas must still be provided by channel or orbit separation or both.

3. THE COMMON-FREQUENCY CONCEPT

The basic idea is that the reduced protection ratio for a digital modulation system may still be achieved by exploiting geographical, orbital and polarisation discrimination while all transmissions are co-channel. In principle, then, all countries could use the whole of any band allocated for HDTV BSS. Provided the EIRP/Hz remained constant, it would not matter what specific parameters each country used, so, for example, each could make its own trade-off of bit rate per programme versus the number of programmes. Thus the concept has some of the flexibility needed in anticipating what will be wanted when HDTV BSS eventually arrives, which will inevitably be some time after the WARC empowered to make an allocation for it.

In the work reported here, there is a significant difference from the example quoted in Section 2.2 above. If both hands of polarisation serve the same service area, then the mutual interference between these two programmes is directly limited (however good the transmitting and receiving antennas) by *atmospheric depolarisation*, even if there are no other transmissions. In the common-frequency concept outlined here, atmospheric depolarisation still plays a significant part; however, a C/I greater than the atmospheric cross-polar discrimination can be achieved in this case, because the opposite hand of polarisation is used with geographical or orbital separation.

4. THE EXAMPLE 'PLAN'

To test the hypothesis that a common frequency approach is of interest, a planning exercise was carried out.

The first thing to note about the example 'plan' is that it is just that: an example, prepared under certain constraints which need not be generally applicable. The 'plan' has been produced manually and intuitively. It follows that the results are unlikely to be the best which can be achieved.

4.1 Assumptions and constraints

4.1.1 Frequency band

The first assumption is that a new band, higher in frequency than 12 GHz, is used. Currently, the whole range from 12.7 to 23 GHz is under consideration, according to Resolution 521 of WARC(ORB)88[6]. This includes the band 22.5 to 23 GHz available to other parts of the world for the BSS, also a band just below that (21.4 to 22 GHz) in which there is currently much interest.

Another possibility is to use the band at 17 GHz which is presently used in the Earth-to-Space direction to provide feeder links for the '12 GHz' BSS satellites.

The scenario presented here was originally conceived to see what use could be made of a band at 17 GHz. However, what is good for efficient use of spectrum at 17 GHz can be used at other frequencies too and the analysis has been extended to include the study of the frequencies above 20 GHz.

This explains some of the decisions in the following example.

4.1.2 Orbit spacing and receiving antenna

Since the frequency is higher than 12 GHz there is some scope for using receiving antennas of narrower beamwidth, with satellites packed more closely around the geostationary orbit. Despite the tendency to use ever-smaller receiving antennas at 12 GHz, a 0.9 m diameter has been retained. At the higher frequencies, with wider bandwidths, higher noise figures, higher atmospheric attenuation and less well-developed high-power satellite TWTs it will be harder to achieve a satisfactory link budget. A relatively large receiving antenna is thus good for both link budget and mutual interference, and HDTV needs the best it can get for both.

Orbit slots separated by 3° were therefore chosen, interleaved with the 6°-separated ones of WARC-77 so that each WARC-77 satellite is 1.5° from an HDTV one. This structure would ensure that HDTV satellites did not interfere with the feeder links of WARC-77 satellites, if HDTV were to use the 17 GHz band.

If bands other than 17 GHz were used for HDTV then this interleaved arrangement would not be necessary. The spacing could be chosen freely as part of an optimisation process.

4.1.3 Orbit position

We have noted that WARC-77 generally chose orbit positions to the West of the service area, in order to avoid eclipses affecting prime viewing time. This was a reasonable thing to do in the context. However, the 'price' (in terms of rain attenuation) of doing this at higher frequencies, especially for more rainy countries, is rather high[7], and in any case it is already more common for satellites to have sufficient battery back-up. Assuming this trend will continue, the effect of eclipses has been neglected in making the 'plan'. What has been done is to try to serve rainier countries, especially the larger ones, from orbit positions of longitude close to those of the service areas so as to minimise the slant-path length and with it the attenuation.

4.1.4 Beam size

The WARC-77 minimum beam size of 0.6° has been kept. Of course at higher frequencies the transmitting antenna would be smaller for the same beam size, so there is possibly scope to modify this restriction, especially as satellite pointing accuracy may improve.

4.1.5 Countries served

If we examine WARC-77 and consider the range of orbit locations from 37° W to 11° E we find the following number of beams:

5 European 'micro-countries' (e.g. Monaco),
35 for other 'European' countries (including the Near East),
53 for Africa.

So there is a high density of required beams per degree of orbital arc.

Some previous planning studies have concentrated on Europe[3] or Europe and North Africa[2]. However, the numbers above show that the real challenge is to deal satisfactorily with Europe and the whole of Africa. The 'hand-made example plan' was therefore intended to include all the countries of Africa and Europe, excluding the USSR and the 'micro-countries'. Purely by mistake, some African countries were omitted, but this should not significantly alter the results. 71 beams were designed in all.

Large countries were not divided into regional beams; partly because the choice of regions really ought to be made by the countries themselves, and partly because leaving them undivided increases the technical challenge and potential flexibility of the 'plan'.

4.1.6 Antenna templates

The WARC-77 transmitting and receiving antenna templates were assumed.

4.2 General structure of the example plan

All allocations are co-channel, by definition.

The reduced protection ratio means that it is possible for countries having small beams to share the same orbit slot and polarisation, provided that they are sufficiently separated. Large countries cannot share in this way.

Countries can share the same orbit slot, with opposite polarisation, with at least a modest geographical separation.

A strategy of producing in effect two interleaved plans for European and African countries (each thus having 6° orbit spacing) was followed as an initial guide, but was not rigorously maintained.

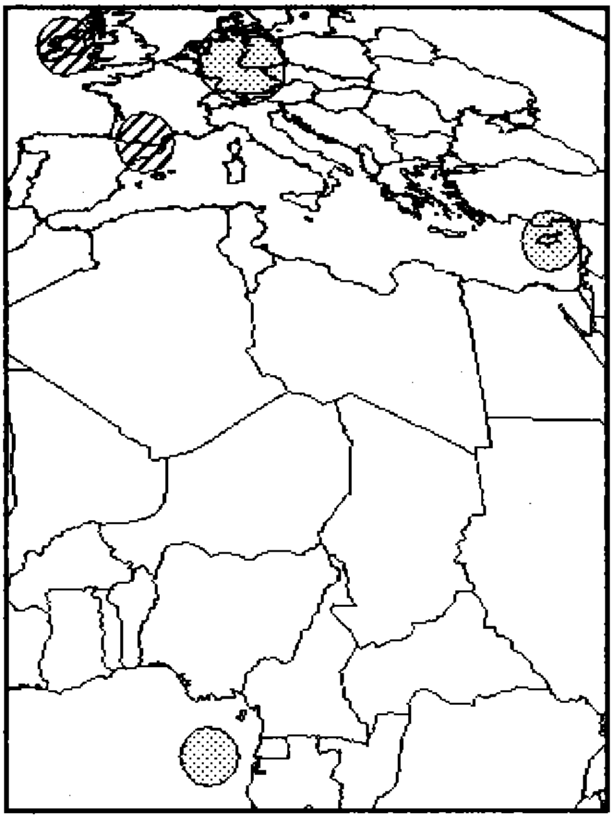

Fig. 1 - The beams from 6.5° E.

Figs. 1 and 2 are presented as examples of the planning. The two hands of polarisation are indicated by the two types of shading.

Fig. 1 shows the beams from the orbit location 6.5° E, which is one of the 'European' set. The biggest

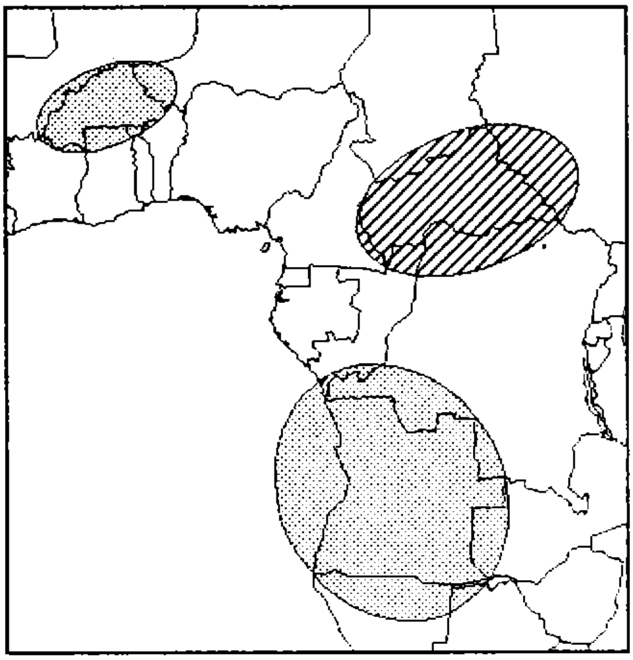

Fig. 2 - The beams from 9.5° E.

main beam serves the Federal Republic of Germany, while all the other beams are of the 0.6° minimum size. The small size means that relatively small separations are sufficient and furthermore an African country (São Tomé and Principé) is included without serious impact on the concept of interleaved European and African plans.

Fig. 2 shows the beams from the adjacent 'African' location, 9.5° E. In this case bigger countries and beams are involved so fewer countries are fitted in.

4.3 How it was made

The 'plan' was constructed intuitively with the aid of the author's EasyMap software for the Atari ST computer. Maps were drawn on-screen showing the views from all the orbit positions. Beams were designed on-screen by manipulation with the mouse to provide a visual 'good fit' to the country in question. The on-screen readout of dB-down with respect to beam centre provided by EasyMap then gave a good idea how far away it was necessary to go before adding another co- or cross-polar beam.

This may sound long-winded but it is very much quicker than specifying polygon points around the border and having the computer invent the ellipses according to some algorithm. It can also lead to better solutions in many cases. There is nothing immutable in the choice of the −3 dB contour for the beam size, and indeed the choice of −4.34 dB gives equal or better service throughout the coverage area. This supports the idea that with countries with awkward shapes it is sometimes better overall to allow some 'protrusions' to lie outside the nominal beam. This permits the beam to be smaller and the resulting gain increase means that for fixed satellite transmitter power most of the country gets better service without disadvantaging the 'protrusion'. This sort of trade-off can be done fairly easily in EasyMap. In fact, with the chosen minimum beam size (0.6°) this did not appear necessary. What was done was to make the beam's −3 dB contour just fit round the country for nominal pointing, compared with WARC-77 where a margin was allowed so that the country always lies within −3 dB contour for all permissible pointing. This means that the designs reported here, done for −3 dB, in practice approach the −4.34 dB case when pointing error is included, as it is in the analysis presented here.

Orbit locations were chosen for the more problematical large or rainy countries first, then the others were fitted around them. Some indication of the scale of the task is given by Figs. 3 and 4, which show all the beams. They no longer appear elliptical because of the map projection, Plate Carrée in this case. The plan itself is detailed in Appendix 2.

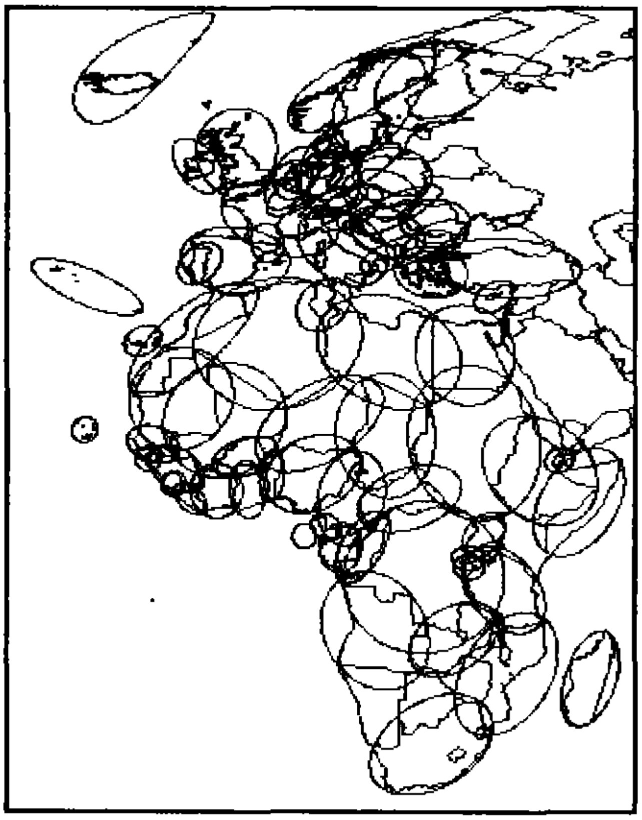

Fig. 3 - All of the beams.

Once the 'plan' was complete, EasyMap was used again to produce sets of 20 test points for each country. These would be used by the analysis program. The test points were chosen arbitrarily on-screen so as to represent all areas of the country in question. Most were along the borders. For the northernmost countries a different view from the 'satellite projection' was used while preparing the test points so that they would be more fairly distributed over the territory. The test points file was then converted into an appropriate format for the analysis program, see Section 5. Fig. 5 illustrates some typical test points.

5. ANALYSIS OF THE EXAMPLE 'PLAN'

5.1 Method

The 'plan' was analysed. The reader is spared the detailed description of the range of software and computers that were necessary to carry out the task.

The plan was tested at 22 GHz for two sizes of receiving dish, 0.7 and 0.9 m diameter. The receiving antenna was assumed to conform to the WARC-77 template for Region 1, with the beamwidth

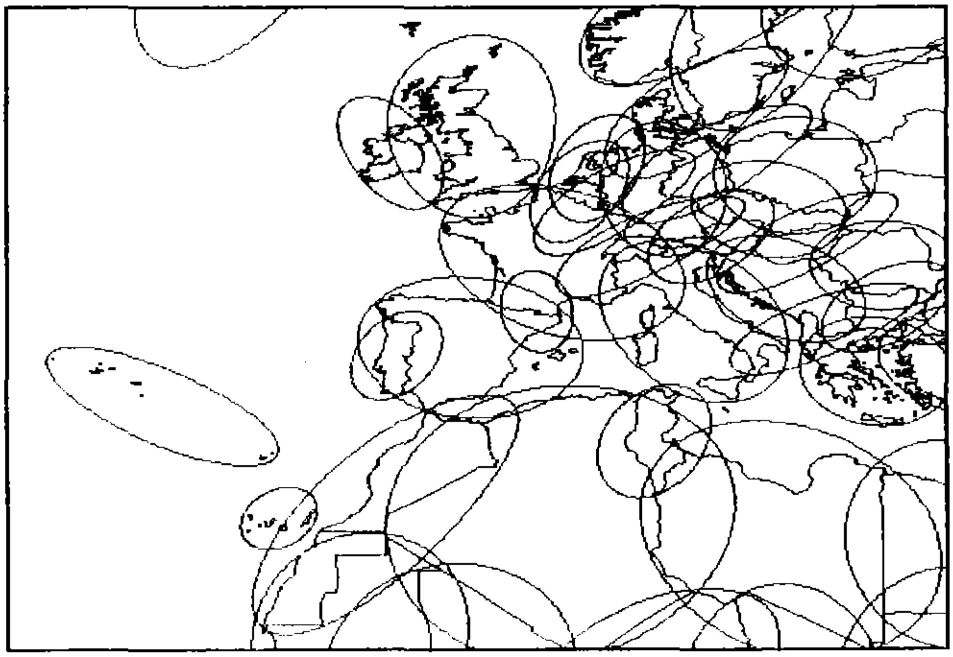

Fig. 4 - Europe and N. Africa.

appropriately scaled for size and frequency. The C/I ratio was calculated for 21 locations for each country, being the 20 points within the country, chosen as described in Section 4.3, plus the aim point of the beam (which in some cases did not lie within the country — usually because it was in the sea). As there were 71 beams, there were thus 1491 test points in all.

5.2 Assumed parameters

Certain values had to be set to complete the scenario which was analysed. These were chosen as follows:

Satellite beam-pointing error:	± 0.1°
Atmospheric depolarisation:	*NONE*

The calculation is worst case, in the sense that for each C/I calculation the wanted satellite is assumed to err in the sense of pointing away from the test point while the interferer errs by pointing towards the point. This cannot occur simultaneously for all

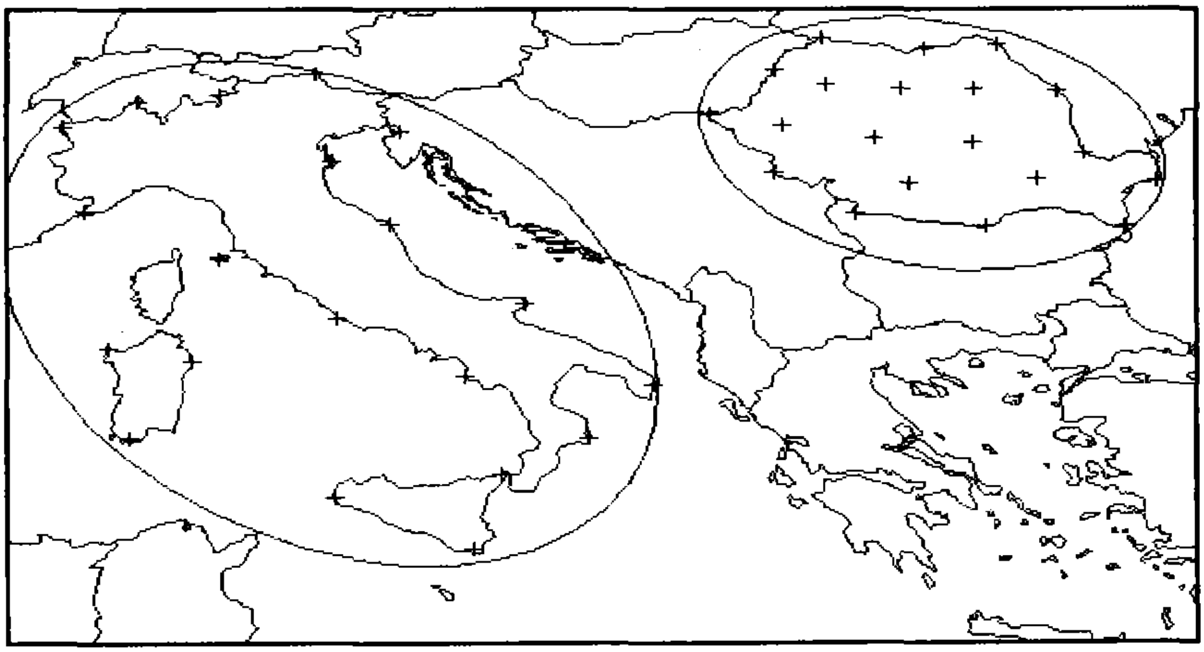

Fig. 5 - The beams for Italy and Romania, showing their respective 20 test points. These countries are served from 12.5° E with opposite polarisation.

satellite combinations and will therefore give somewhat pessimistic results.

All transmissions were assumed to have the same beam-centre EIRP.

5.3 Results

These are summarised in Fig. 6.

The Figure shows that virtually 100% of test points achieve a C/I better than 15 dB, whichever antenna size is used. (The few exceptions merit closer scrutiny when time permits; the cause is probably over-zealous assignment of test points to places such as off-coast islands which were not considered when the beams themselves were defined. The difference between 0.7 m and 0.9 m diameter receiving antennas is not great; there is a difference in C/I of about 1 dB for the significant case of 99% of test points. As previously noted, considerations of carrier-to-noise ratio C/N will in any case favour the larger dish.

6. DISCUSSION

It is usual to treat C/I as equivalent noise which degrades the link budget; however, we should note Ref. 4 which shows that this is pessimistic for the case of single or dominant interferers. The acceptable level of C/I depends on the modulation system chosen (e.g. the higher the bits/symbol the higher the required C/I, in general) and also on the trade-off made between noise and interference in the link budget.

There is thus no single clear target protection ratio with which to assess this plan, and that is the reason for the form of presentation used in Fig. 6. Appendix 1 considers an example (convolutionally-coded QPSK with Viterbi decoding) where the degradation caused by a C/I as low as 10 dB might well be acceptable. This would be less true where there are multiple interferers causing a more noise-like behaviour, so this figure (C/I = 10 dB) is thus perhaps optimistically low for our purpose. The range up to 20 dB has been considered in other studies.

The results are thus encouraging. We can see that a plan of this form need not disturb the link budget very much. Indeed, it means that multi-state modulation systems which offer higher spectral efficiency may be possible.

We should note that the plan has been analysed 'worst-case' as regards satellite pointing error, since the worst scenario has been selected test-point-by-test-point. Such a scenario cannot apply to all points simultaneously. No optimisation of the plan by adjusting EIRPs has been performed. Furthermore, this is only the first attempt at designing the 'plan'. Further study of the detail of the analysis might reveal obvious scope for improvement. Perhaps a computer optimisation strategy could be devised. Many countries could

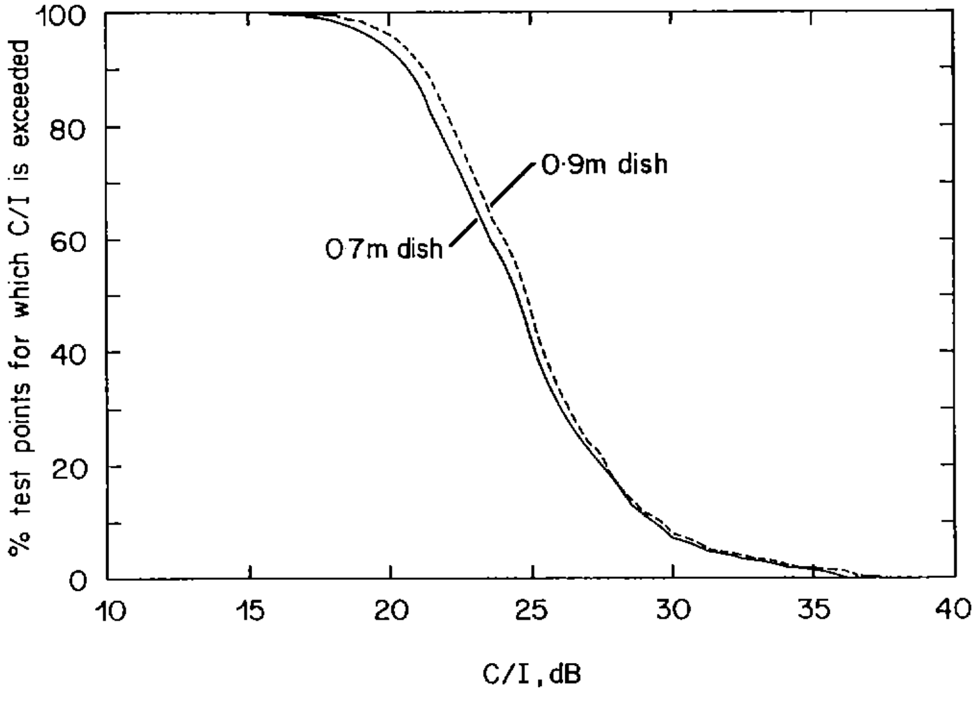

Fig. 6 - The performance of the plan, assessed at 22 GHz for 0.7 and 0.9 m dia. dishes.

use a beam having axes smaller than the value of 0.6° taken as the lower limit in this study.

The plan has been analysed as if only co-channel interference occurs. This assumes that all of a band is given over to one HDTV "channel" (which could convey many programmes, depending on the bit-rate chosen). Of course all countries need not use all of the band. As long as the EIRP per Hertz remains the same then the interference to other countries will be less than or equal to that analysed here. Similarly, for those countries which were given a single beam despite the large size of the country, it would only improve the interference to others if the beam were made smaller — or shaped.

There is thus a lot of flexibility. For example, large countries for which the power required to serve all their territory is at present embarrassingly high can start by using smaller beams and/or a lesser bit-rate (and thus only part-fill the band). As long as a common value of EIRP/Hz could be agreed upon then the details of each country's implementation can be decided in the light of the other constraints which apply at the time of introduction of a service.

The results have been quoted for 22 GHz. However it is easy to infer the following equivalences for receiving antenna beamwidths:

0.9 m at 22 GHz is equivalent to 1.13 m at 17.5 GHz,

and

0.7 m at 22 GHz is equivalent to 0.9 m at 17.5 GHz.

The plan is therefore surprisingly successful as a way to exploit the 17 GHz feeder-link band in 'reverse-band working'.

It is of interest to assess the spectrum efficiency of this scheme, and to compare it with that of other proposals, particularly analogue ones. To do this we must make some assumptions about the details of both the source-coding and the combination of channel-coding and modulation schemes. Let us suppose that an HDTV signal (comprising picture, sound and associated data) can be accommodated within 140 Mbit/s by the use of suitable source coding. Various modulation schemes (e.g. trellis-coded 8-PSK) could be proposed which would accommodate this bit rate within about 100 MHz while remaining compatible with the order of C/I we have considered. It then follows that to provide one HDTV programme per country (or similarly-sized area) would require approximately 100 MHz using the digitally-modulated common-frequency approach outlined here. Ref. 2 suggests that the use of analogue modulation for wide-band HDTV at 23 GHz would require 150-200 MHz. Finally we may compare these figures with those obtained by the WARC-77 12 GHz Plan, which (for Europe at least) gave five programmes per country within a band of 800 MHz width, i.e. 160 MHz per programme.

7. CONCLUSIONS

An example 'plan' has been described which would clearly support the broadcasting of HDTV to real countries, using digital modulation in either the 17 or 22 GHz band. The trade-off of dish size versus interference has been illustrated for two sizes. The results are very encouraging despite being evaluated in a rather pessimistic manner with no optimisation of the plan by adjusting EIRPs.

The example suggests a relatively flexible approach to planning. Each country could be assigned an orbital position and polarisation. All countries could use the whole of the allocated frequency band subject only to a limit on power spectral density, i.e. EIRP/Hz. The bit rate, bandwidth, modulation scheme and so on could then be decided by each country according to its particular constraints at the time of introducing a service. Of course all the usual commercial and political reasons for standardisation — or not — would still apply, but there is no need for them to be enshrined in the Radio Regulations in advance.

The digital common-frequency concept offers greater spectral efficiency than other techniques.

8. ACKNOWLEDGEMENT

The author gratefully acknowledges the contribution of David Morton who orchestrated the development of the software needed to analyse the plan.

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APPENDIX 1

An Example of the Improved Carrier-to-interference Ratios Possible when using a Digital Modulation System with Coding*

The experimental configuration is shown in Fig. A1.1. With this it is possible to feed the QPSK (quaternary phase shift keying) modulator with either differentially-coded data or convolutionally-coded data. For both these coding systems the bit-error ratio (BER) was measured over a range of E_b/N_o and carrier-to-interference (C/I) ratios. Here E_b/N_o stands for the energy per information bit over the spectral noise density. The co-channel interferer was a single digital interferer operating at the same bit rate as the wanted signal. The interferer also had the same spectral shaping but was modulated with a different data sequence to reduce any correlation between the two.

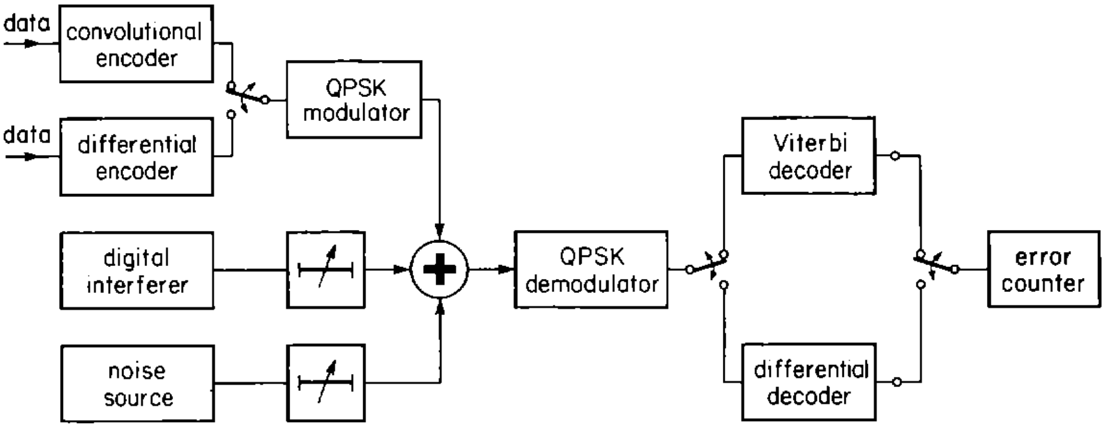

Fig. A1.1 - Experimental configuration.

The Viterbi decoder had a constraint length of six bits and had a rate of 1/2. It quantised the demodulated data to eight levels and so could be considered to be using soft-decision decoding. Fig. A1.2 gives the results of the experiment. The coding gains quoted for no co-channel interference (C/I = ∞) are typical for a Viterbi decoder

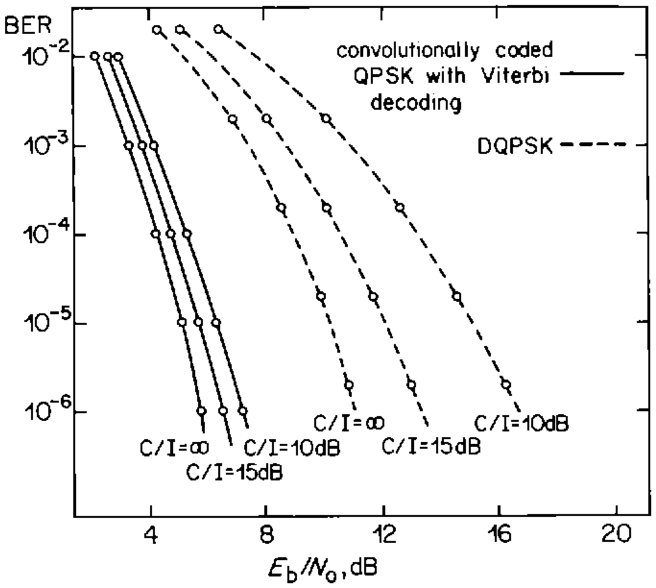

Fig. A1.2 - Error performance of convolutionally coded QPSK with Viterbi decoding and conventional DQPSK in the presence of co-channel interference and random noise.

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* This work was carried out by J.D. Newland.

of this complexity. It is more interesting to note that the interference produces only a small degradation in the Viterbi decoder's performance and even at a C/I ratio of 10 dB there is a degradation of no more than 1.5 dB at all points. This contrasts strongly with the differentially-coded data at the same C/I ratio; its performance is degraded severely at the lower error rates.

If more than one interferer is contributing to the interference power then the coding gain of the Viterbi decoder will not be so high. This is because as the number of independent interferers increases, the probability density function of the interference approaches that of gaussian noise. Hence for a large number of independent interferers the coding gain would tend to that obtained when a noise power equal to the total interference power is added.

These results show that using Viterbi decoding reduces the sensitivity of the BER of QPSK to co-channel interference.

APPENDIX 2

Details of the Example 'Plan'

The details of the example plan are given in tabular form below. The terms are used according to the same definitions as Ref. 1.

Country (ITU code)	Orbit Locn. °E	Aim point Longitude °E	Aim point Latitude °N	Major Axis °	Minor Axis °	Rotation °	Polarisation
ALG	−38.5	1.43	27.54	3.07	1.95	131	1
SEN	−38.5	−14.5	13.96	1.19	0.80	151	2
CVI	−35.5	−24.07	15.97	0.60	0.60	0	1
POR	−35.5	− 8.05	39.51	0.74	0.60	125	2
AZR	−35.5	−23.64	36.03	2.40	0.60	158	2
ISL	−35.5	−19.40	64.88	0.74	0.60	173	1
SUI	−35.5	8.23	46.75	0.60	0.60	0	2
GNB	−32.5	−15.05	12.01	0.60	0.60	0	1
CTI	−32.5	− 5.58	7.47	1.33	1.06	104	2
TUN	−32.5	9.27	33.62	1.09	0.60	120	2
CNR	−29.5	−15.95	28.53	0.75	0.60	15	1
E	−29.5	− 3.28	39.88	1.90	0.96	159	1
LUX	−29.5	6.10	49.72	0.60	0.60	0	2
MRC	−26.5	− 9.85	28.21	2.87	1.36	47	2
GHA	−26.5	− 1.20	7.68	1.41	0.74	100	1
TCD	−26.5	17.48	14.97	2.92	1.35	108	1
DDR	−23.5	12.69	52.24	0.64	0.60	150	1
G	−23.5	− 2.98	54.44	1.34	0.66	145	2
NIG	−20.5	7.67	9.71	1.99	1.76	41	2
F	−17.5	3.20	45.56	2.09	0.84	158	1
LBR	−14.5	− 9.12	6.36	0.97	0.60	137	2
CME	−14.5	13.19	6.28	2.30	1.39	87	1
BEL	−11.5	4.32	50.51	0.60	0.60	164	2
NGR	− 8.5	8.36	16.65	2.94	1.86	32	1
GNE	− 8.5	9.88	2.31	0.76	0.60	135	2
MTN	− 8.5	−10.50	20.11	2.50	2.21	34	2
S	− 5.5	16.07	60.88	1.00	0.60	139	2
HOL	− 5.5	5.57	52.08	0.60	0.60	139	1
RRW	− 5.5	29.89	− 1.97	0.60	0.60	139	1
BEN	− 5.5	2.22	9.61	1.22	0.60	90	1
GAB	− 2.5	11.89	− 0.53	1.23	1.00	80	1
LBY	− 2.5	18.34	26.63	3.25	2.00	149	2
FNL	0.5	24.98	64.45	1.12	0.60	160	1
BUR	0.5	29.96	− 3.25	0.60	0.60	160	2
MLI	3.5	− 4.37	17.14	2.97	2.53	30	2
COG	3.5	14.94	− 0.47	2.01	0.98	60	2
SDN	3.5	30.10	13.88	3.76	2.51	113	1
STP	6.5	6.86	1.05	0.60	0.60	153	1
BFA	9.5	− 1.49	12.25	1.63	0.86	21	1
AGL	9.5	16.70	−12.00	2.93	2.47	118	1
CAF	9.5	21.44	6.34	2.55	1.52	19	2
EGY	15.5	29.27	26.36	2.34	1.86	136	1
ZMB	15.5	27.79	−13.26	2.38	1.44	34	2
DJI	18.5	42.59	11.83	0.60	0.60	170	1
RSA	21.5	24.83	−27.82	2.87	1.75	29	2
ZAI	21.5	23.59	− 4.57	3.97	3.74	9	1
UGA	27.5	32.03	1.33	1.28	0.87	50	2
TZA	36.5	34.97	− 6.31	2.46	1.65	130	1
ETH	39.5	39.94	10.18	3.05	2.37	141	2
MOZ	41.5	35.46	−17.87	3.04	2.05	60	2
SOM	45.5	45.39	5.79	2.94	1.88	57	1

Appendix 2 (cont.)

Country (ITU code)	Orbit Locn. °E	Aim point		Major Axis °	Minor Axis °	Rotation °	Polarisation
		Longitude °E	Latitude °N				
MDG	48.5	47.06	−18.77	2.27	1.18	71	2
ALB	−29.5	19.99	41.19	0.60	0.60	0	2
HNG	−23.5	18.94	47.00	0.60	0.60	0	2
SRL	−26.5	−11.60	8.42	0.60	0.60	0	2
GUI	−20.5	−11.06	10.44	1.52	0.95	144	1
DNK	−17.5	11.39	55.63	0.68	0.60	159	2
NOR	−11.5	13.03	63.58	0.92	0.61	10	1
AUT	−11.5	13.13	47.48	0.74	0.60	176	1
BUL	−11.5	24.93	42.72	0.73	0.60	151	2
YUG	0.5	18.44	43.94	1.43	0.60	157	1
POL	0.5	18.97	51.56	1.16	0.60	161	2
AND	6.5	1.59	42.50	0.60	0.60	0	2
IRL	6.5	− 8.02	53.12	0.60	0.60	0	2
D	6.5	10.18	50.51	0.93	0.77	155	1
CYP	6.5	33.38	34.97	0.60	0.60	0	1
I	12.5	12.39	41.53	1.68	1.11	156	2
ROU	12.5	24.97	45.56	1.14	0.60	171	1
TCH	18.5	17.36	49.34	1.13	0.60	175	2
GRC	18.5	24.49	38.34	1.40	0.87	168	1
TUR	24.5	34.95	38.84	2.72	0.99	174	2

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